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Neutronics Design of a Thorium-Fueled Fission Blanket for LIFE (Laser Inertial Fusion-based Energy)

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Abstract – *The Laser Inertial Fusion-based Energy (LIFE) project at LLNL includes development of hybrid fusion-fission systems for energy generation. These hybrid LIFE engines use high-energy neutrons from laser-based inertial confinement fusion to drive a subcritical blanket of fission fuel that surrounds the fusion chamber. The fission blanket contains TRISO fuel particles packed into pebbles in a flowing bed geometry cooled by a molten salt (flibe). LIFE engines using a thorium fuel cycle provide potential improvements in overall fuel cycle performance and resource utilization compared to using depleted uranium (DU) and may minimize waste repository and proliferation concerns. A preliminary engine design with an initial loading of 40 metric tons of thorium can maintain a power level of 2000 MW_{th} for about 55 years, at which point the fuel reaches an average burnup level of about 75% FIMA. Acceptable performance was achieved without using any zero-flux environment "cooling periods" to allow ^{233}Pa to decay to ^{233}U; thorium undergoes constant irradiation in this LIFE engine design to minimize proliferation risks and fuel inventory. Vast reductions in end-of-life (EOL) transuranic (TRU) inventories compared to those produced by a similar uranium system suggest reduced proliferation risks. Decay heat generation in discharge fuel appears lower for a thorium LIFE engine than a DU engine but differences in radioactive ingestion hazard are less conclusive. Future efforts on development of thorium-fueled LIFE fission blankets engine development will include design optimization, fuel performance analysis work, and further waste disposal and nonproliferation analyses.*

I. INTRODUCTION

Laser Inertial Fusion-based Energy (LIFE) systems use laser-driven inertial confinement fusion (ICF) to produce energy and electricity.[1] Laser beams illuminate deuterium-tritium targets at the center of a spherical chamber with a repetition rate of about 13 Hz, igniting (D,T) fusion events that each produce 17.6 MeV of total energy including a 14.1 MeV neutron. Design options include pure fusion systems that directly harvest energy from the fusion events as well as hybrid fusion-fission systems that use high-energy fusion neutrons to drive a subcritical fission blanket wrapped around the chamber. Previous studies established a baseline design using depleted uranium (DU) as a fission blanket fuel.[2,3] This paper provides preliminary results for a thorium-fueled LIFE fission blanket and analyzes some of the differences between DU and thorium blanket designs.

II. HYBRID LIFE ENGINES

The National Ignition Facility (NIF) at LLNL will soon demonstrate the scientific feasibility of laser ICF ignition.[1] The LIFE concept builds upon this and provides a transition to developing real inertial fusion energy (IFE) systems. Reasons to pursue the development of hybrid fusion-fission LIFE engines include fission safety benefits from having a source-driven subcritical system, the ability to run a fission system with no enrichment or reprocessing, and using the power gains of the fission blanket to achieve an economically attractive stepping stone technology to gain operational experience with fusion power plants before advances in driver technologies and target designs enable reasonable pure fusion plants.

Fusion (14.1 MeV) neutrons are born at the center of the LIFE engine, travel through a neutron multiplier layer, and then proceed into the fission blanket. The laser driver assumed in our current analyses provides NIF-like illumination and the target undergoes NIF-like hot-spot ignition.[2] The fission blanket contains TRISO particles packed in pebbles and flibe (2 LiF + BeF_2) molten salt coolant.[5,6] This study examines LIFE engine designs with 500 MW_{th} of fusion power, a total system power of 2000 MW_{th}, and requires each LIFE engine to be tritium self-sufficient (i.e., each engine must breed enough tritium to fuel its fusion plant).

Given that LIFE engines consist of a set of concentric spherical shells separated structural walls, shown in Fig. 1, the system can best be described in terms of its radial build. The inner sphere serves as a fusion chamber; hohlraum targets are injected into this chamber and ignited at its center while the rest of the chamber is filled with xenon gas to protect the chamber wall from ions and x-rays emitted from the fusion target. The fusion chamber wall, called the first wall, consists of an oxide-dispersion strengthened (ODS) ferritic steel with a 250 μm tungsten armor on the front of it facing the inside of the fusion chamber. A layer of lithium-lead surrounds the first wall and serves as a dedicated first wall coolant. These components are surrounded by a fission system. Its first layer consists of a flibe coolant injection plenum; from here, coolant flows radially outward through a neutron multiplication region loaded with beryllium pebbles, the fuel and reflector regions of the fission blanket loaded with fuel and graphite pebbles respectively, and then recollects in a coolant extraction plenum and leaves the LIFE engine. The pebble regions (neutron multiplier, fuel, and reflector regions) all consist of packed beds with 60% of their volume occupied by pebbles and the remaining 40% of their volume occupied by coolant. ODS steel structural walls separate each spherical shell, with the use of 12YWT steel currently assumed; use of a perforated wall is assumed wherever flibe flows through radially.[4]

Table I provides details for the composition, densities, and physical dimensions of each region for a thorium-fueled hybrid LIFE engine that will be described in further detail later. Previous work describes more explicitly the reasons for some of the choices of materials and densities.[3,4] Tritium breeding in a LIFE engine occurs primarily through (n,T) reactions with ^{6}Li in the flibe and LiPb coolants. Controlling the isotopic ratio of ^{6}Li to ^{7}Li in each coolant governs the production rate of tritium and the resulting Tritium Breeding Ratio (TBR), which expresses the ratio of tritium production divided by tritium consumed by fusion, and the fission power.

An updated thermal-mechanical design using modular construction design principles and non-spherical components exists but is not modeled in current neutronics studies.

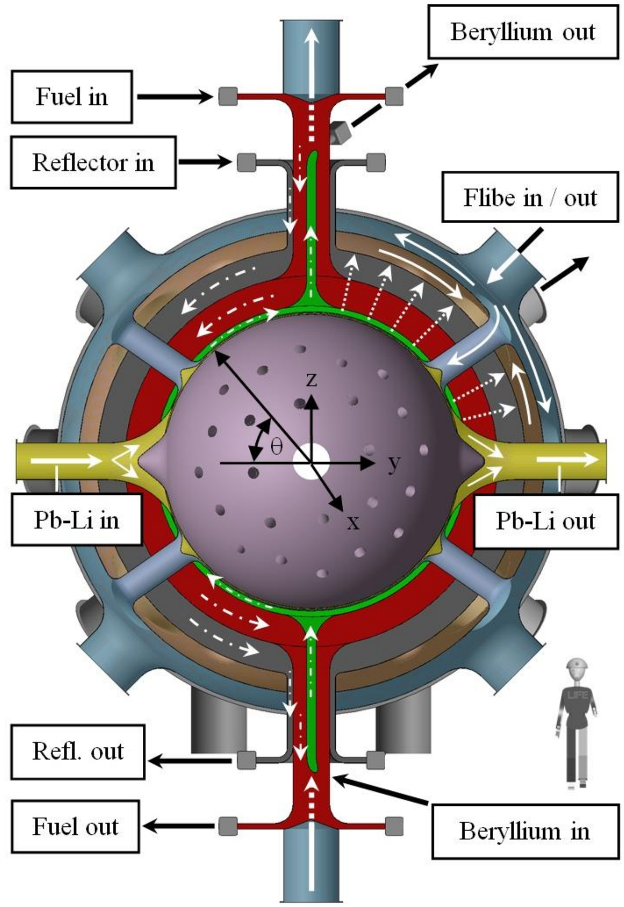

Fig. 1. Cross-section view of a hybrid LIFE engine showing internal structures, coolant flows, and pebble flows[4]

TABLE I

Radial Build for a Thorium-fueled Hybrid LIFE Engine

Component	Material	Density [g/cc]	Thickness [cm]
Fusion Chamber	Xe Fill Gas	6.5×10^{-6}	250 (radius)
Armor	Tungsten	19.3	0.025
First Wall (FW)	ODS Steel	8.0	0.275
FW Coolant	LiPb	9.4	3
Injection Plenum	FLiBe	2.0	3
Multiplier	60% Be 40% FLiBe	1.94 2.0	16
Fission Blanket	60% Fuel 40% FLiBe	- 2.0	98.3
Reflector	60% Graphite 40% FLiBe	- 2.0	75

The multiplier region consists of beryllium (Be) pebbles in flibe coolant and accomplishes both tritium breeding and neutron multiplication through (n,2n) reactions of fast neutrons (mostly E > ~2.7 MeV) and ^{9}Be. The fission blanket uses TRISO fuel particles randomly packed into 2 cm diameter graphite pebbles at a 30% packing fraction with design parameters as specified by Table II.[a]

TABLE II

Design Parameters for Thorium-fueled LIFE TRISO Particles [a]

Layer	Density [g/cc]	Thickness [μm]
Kernel (ThCO)	9.86	300 (radius)
Buffer (porous C)	1.1	102
IPyC	1.95	30
SiC	3.2	60
OPyC	1.95	20
Matrix (graphite)	1.7	-

Existing analyses assume the graphite pebbles to be pure graphite with some tungsten added at pebble core to handle buoyancy effects; future analyses may examine whether a coating or shell would have to be put on the fuel and reflector pebbles to mitigate possible corrosion, mechanical erosion, or time-dependent buoyancy concerns.

III. METHODOLOGY

The neutron transport and burnup analysis calculations utilize the MONTEBURNS 2.0 burnup package, which couples MCNP5 Version 1.42 and ORIGEN 2.2.[8,9,10] The Life Neutronics Control (LNC) code, developed at LLNL, controls MONTEBURNS executions while automatically adjusting the ^{6}Li/^{7}Li ratio in each coolant to satisfy three user-specified criteria: TBR range for each phase, plateau power range, and minimum accumulated tritium inventory (requiring a minimum inventory of 0 kg to ensure tritium self-sufficiency).[3]

The burnup analyses in this study utilize an MCNP input with double-heterogeneous fuel modeling: lattice geometry is used to pack pebbles into the fuel blanket region and TRISO fuel particle kernels into each pebble. Multiple independent studies available in the literature demonstrate the importance of modeling the double-heterogeneous nature of TRISO fuel in pebbles and that using a regular lattice in MCNP5 to place fuel pebbles and kernels adequately captures physics effects.[11,12] It should be mentioned that the burnup analyses in this study assume a single burnup zone; this represents a fair approximation if fuel pebbles have a short residence time during each pass in the fission blanket and are randomly mixed before being reinserted but should be adjusted to a larger number of depletion zones in future studies to accurately capture the details of variations in neutron flux magnitude and spectrum and other parameters that vary with radial position in the system. Homogenous modeling was used for all other regions, including the neutron multiplier and reflector regions which respectively contain beryllium and graphite pebbles; previous LIFE studies investigating the effects of treating the multiplier and reflector regions as homogenous zones found the net effect in the DU system to be less than 1% difference in reaction rates.[13] Openings in ODS structural walls needed to allow radial flow of flibe coolant are accounted for by adjusting the density of the 12YWT steel from 8 g/cm^{3} to 6 g/cm^{3}. Fig. 2 depicts the MCNP modeling used for homogenizing the neutron multiplier ("Be/Flibe") zone as well as the heterogeneity of the fuel region, with magnified views of a single pebble surrounded by flibe and kernels in the pebble matrix.

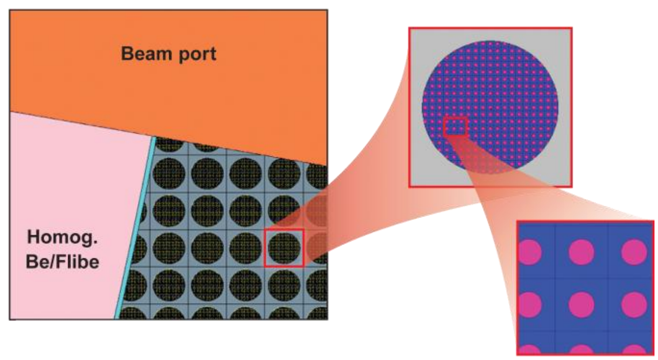

Fig. 2. Illustration of MCNP lattice models used for fuel kernels in a pebble and pebbles in a bed in a hybrid LIFE fission blanket

Previous publications describing the neutronic design of hybrid LIFE engines with fertile fuels characterized in great detail the three main phases of operation: ramp-up, plateau, and incineration.[3] During ramp-up, fertile fuels are transformed into fissile fuels (e.g., ^{232}Th becomes ^{233}U or ^{238}U becomes ^{239}Pu) and total system power increases. The plateau phase involves continued conversion of fertile fuels into fissile fuels and sustained operation within the plateau power range; system power level is controlled using ^{6}Li as a neutron poison early in life and then using excess tritium to maintain system power later in life. The incineration phase involves operation at a reduced power level so that fusion neutrons can be used more extensively for tritium production and heavy metal transmutation.

[a] The TRISO particle dimensions documented here and used in the analyses of this paper differ slightly from those published previously;[3,4] these updated dimensions reflect feedback from subsequent LIFE fuel performance work.[7]

IV. THORIUM-FUELED FISSION BLANKETS

A recent International Atomic Energy Agency (IAEA) technical report detailed historical interest in thorium nuclear fuels and data available from reactor operations and fuel development efforts. It also detailed the motivations behind recent efforts to pursue a thorium fuel cycle in the nuclear energy sector.[14] Other publications have suggested or examined the use of thorium nuclear fuel as well.[15,16]

Improvements in resource utilization and possible reductions in waste storage and proliferation risks provide major motivating factors for investigating a thorium-fueled LIFE engine, and indeed motivate the evaluation of a thorium fuel cycle for other nuclear energy systems as well.[14,15,16] The natural abundance of thorium at least equals that of uranium and some estimates indicate thorium may be 3 to 4 times more abundant; furthermore, using thorium as a fuel offers significant improvements in overall utilization when compared to the enriched uranium fuels used in most nuclear energy systems since nearly all of the ore extracted from the ground can be used without any losses to enrichment tails.[14] The use of ^{233}U as the main fission fuel in a thorium system leads to much lower production rate of transuranic (TRU) nuclides (species with an atomic number greater than 92) than in uranium fuel systems; this offers possible improvements for waste storage and nonproliferation as the majority of long-term waste storage hazards are TRU nuclides and plutonium (atomic number of 94) represents a major proliferation risk.

To facilitate an accurate and fair comparison of thorium and DU systems, the thorium engine described in this paper used a previously established reference concept for a DU LIFE engine as a starting point.[3,17] This DU design had an initial heavy metal loading of 40 metric tons (MT) of DU in the form of UCO fuel kernels, a 30% packing fraction of TRISO particle in the fuel pebbles, a beryllium neutron multiplier region with a thickness of 16 cm, and a 75 cm thick reflector region with graphite pebbles in flibe. The UCO kernels (10.5 g/cc) were changed to ThCO (9.86 g/cc) and the fuel blanket thickness increased from 86.26 cm (DU system) to 98.3 cm (thorium system) to conserve an initial heavy metal loading of 40 MT. All other design parameters, including user-specified minimum tritium mass and plateau power range, were held constant between the two cases. Table I and Table II provide the thorium LIFE engine radial build and fuel design parameters, respectively.

Preliminary results for a thorium-fueled LIFE fission blanket indicate acceptable performance. The engine has a ramp-up period of just under 2 years, reaches a burnup level of about 76% FIMA (percent fissions per initial metal atom) at its end of plateau (EOP) after about 53 years of level power, and achieves a burnup level of 99% FIMA in its incineration phase after about 145 cumulative years of operation. Fig. 3 and Fig. 4 show how the total system power for a thorium LIFE engine evolves as a function of burnup level in the fuel and time of operation, respectively.

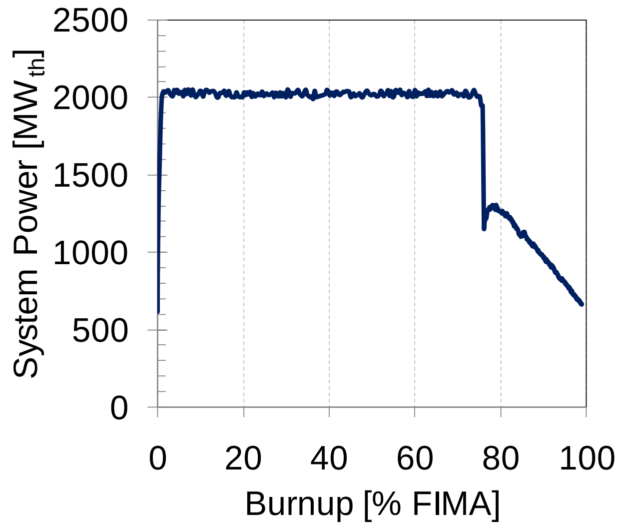

Fig. 3. System power as a function of burnup level for a thorium-fueled LIFE engine

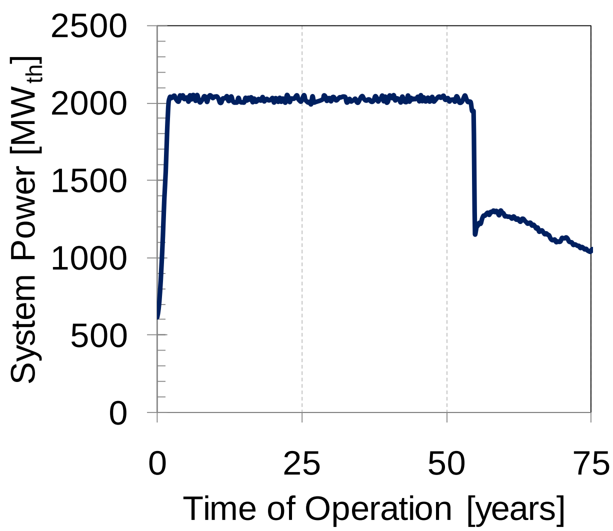

Fig. 4. System power as a function of time (in years) for a thorium-fueled LIFE engine

Fig. 4 represents a LIFE engine using a single initial loading of fuel with continual full mixing of fuel pebbles; various fuel shuffling schemes offer improvements upon this and could enable better performance at higher burnup levels by extending the plateau or increasing incineration phase power levels.

Tritium production and consumption play important roles in a LIFE engine. Fig. 5 shows the burnup-dependent TBR corresponding to the power curve in Fig. 3.

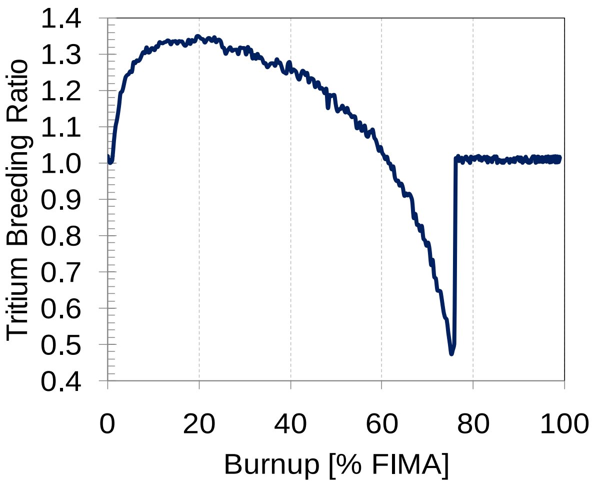

Fig. 5. Burnup-dependent TBR for a thorium LIFE engine

Fig. 6 presents key nuclide inventories as a function of burnup in units of absolute mass (kilograms) while Fig. 7 shows the burnup-dependent fractional composition. Fissile isotopes build up early in life, peak at different times based upon the production and destruction processes involved, and then decrease as their production term falls away; however, total fissile inventory for the system consistently represents around 8-10% of the heavy metal mass during the plateau phase. A discontinuity at ~76% FIMA corresponds to the transition from plateau phase operation to incineration phase, which involves insertion of large amounts of ^{6}Li and a sharp decrease in fission power and neutron flux. This decreased flux term leads to a lower production rate of ^{233}Pa from ^{232}Th but increases the fraction of ^{233}Pa that decays to ^{233}U, as demonstrated by the sharp decrease in ^{233}Pa mass and slight increase in ^{233}U mass at that point.

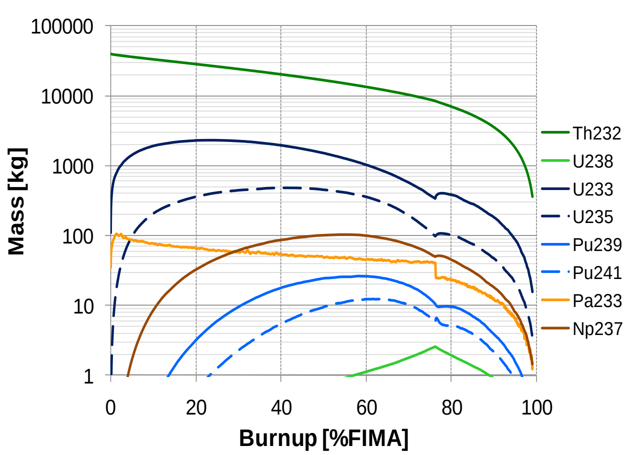

Fig. 6. Absolute masses (in units of kg) for several key nuclides as a function of burnup level for a thorium LIFE engine

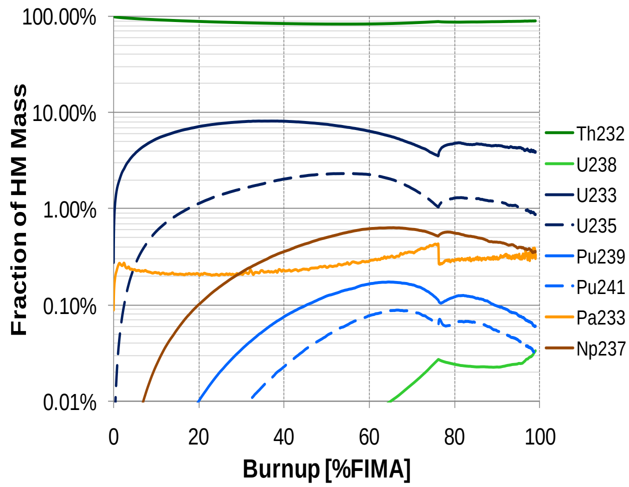

Fig. 7. Fraction of heavy metal mass for several key nuclides as a function of burnup level for a thorium LIFE engine

V. COMPARISON TO DU SYSTEMS

The neutronic performance achieved by this preliminary thorium LIFE engine design roughly matches the performance achieved using DU. Fig. 8 and Fig. 9 compare system power curves for thorium and DU LIFE engines as a function of time of operation (in years) and burnup level (in %FIMA), respectively. As seen in Fig. 9, the thorium system has a slightly lower end of plateau burnup level. Fig. 10 and Fig. 11 show comparisons of burnup-dependent TBR and tritium mass inventories.

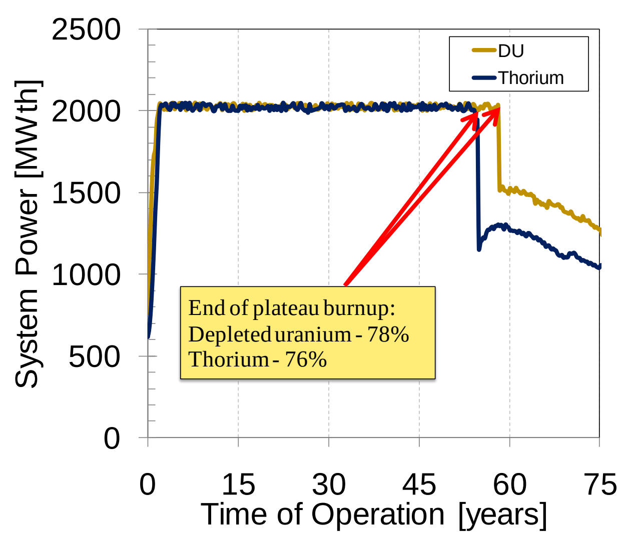

Fig. 8. A comparison of system power as a function of time of operation for thorium and DU LIFE engines

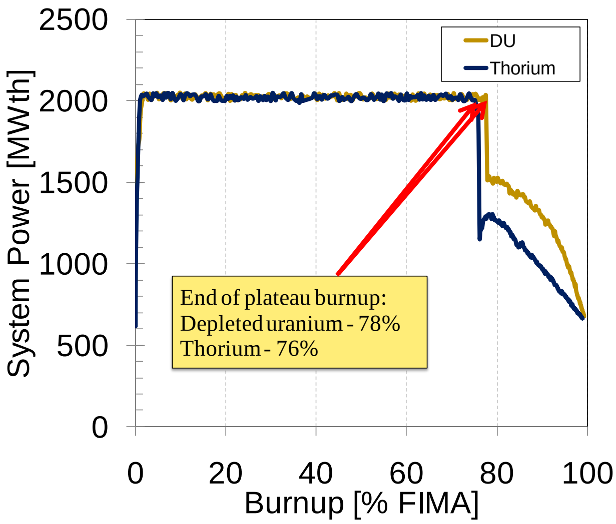

Fig. 9. A comparison of system power as a function of fuel burnup level for thorium and DU LIFE engines

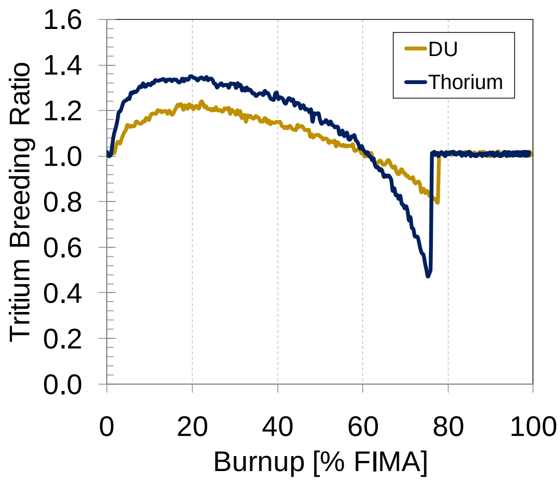

Fig. 10. Tritium breeding ratio as a function of burnup level for thorium and DU LIFE engine designs

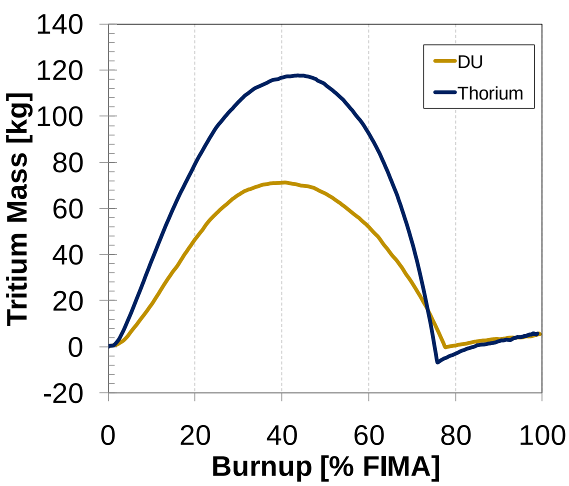

Fig. 11. Tritium inventory mass (in units of kg) as a function of burnup level for thorium and DU LIFE engine designs

The thorium LIFE engine reaches a higher peak TBR value and higher tritium inventory than the DU system but exhibits a sharp decrease in TBR and tritium inventory values late in life, likely due to the conversion ratio falling off rapidly.

One key benefit of using thorium fuel instead of DU rests in the differences of discharge masses for key nuclides between the two systems. Fig. 12 shows the mass differences present when using the fuel composition for a 50% FIMA burnup level in each system. While this is a single point in time, the results reflect an overall trend of the discharge mass differences between thorium and DU systems over a wide range of discharge burnup levels.

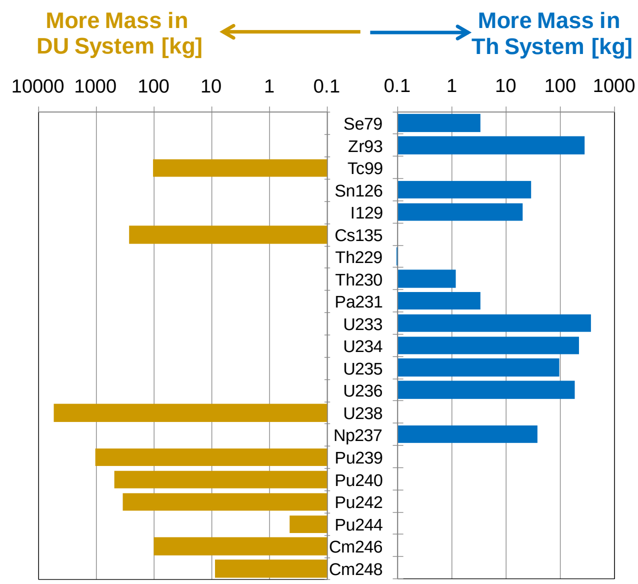

Fig. 12. Mass differences for key nuclides between thorium and DU LIFE engines at 50% burnup in each system

The thorium system yields drastically reduced TRU inventories but significantly higher uranium discharge masses. Differences in the fission product yields of the two systems result in thorium producing more of some nuclides (e.g., ^{93}Zr and ^{129}I) and DU producing more of others (e.g., ^{99}Tc and ^{135}Cs). ORIGEN2.2 calculations are used to assess the radioactive decay heating and radioactive ingestion hazards from EOP fuel compositions for thorium and DU. Fig. 13 shows the decay heating and Fig. 14 shows the radioactive ingestion hazard. Both plots normalize results to the amount of energy (Gigawatt-days) produced during operation. The radioactivity analyses use the full nuclide inventory without accounting for solubility limits or other barriers. Default ORIGEN2.2 values for Maximum Permissible Concentrations (MPCs) were used; updated MPCs exist but no data library file was available for use and the main purpose of these analyses was a side-by-side comparison of thorium and DU rather than a complete repository analysis.

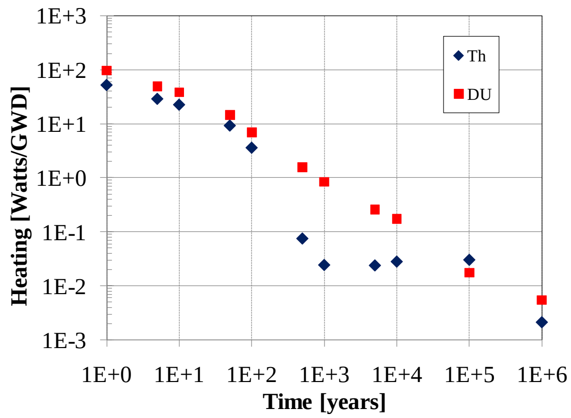

Fig. 13. Radioactive decay heating as a function of decay time for discharge fuel from thorium and DU LIFE engine designs

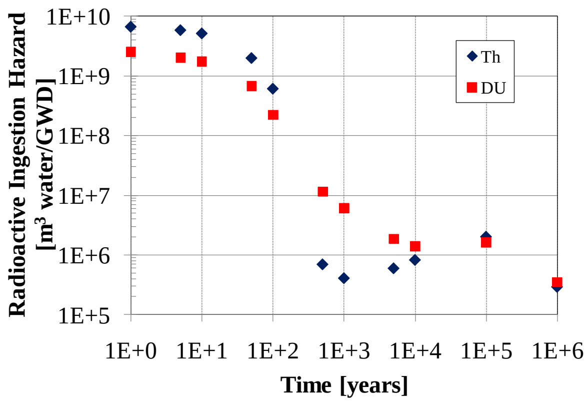

Fig. 14. Radioactive Ingestion Hazard as a function of decay time for discharge fuel from thorium and DU LIFE engine designs

Thorium has a slightly reduced decay heat load at nearly all future times. Radioactive ingestion hazards posed by thorium and DU are more complex; thorium poses a greater hazard until 100 to 200 years after discharge and thereafter is generally less hazardous. This short-term elevated hazard stems largely from ^{90}Sr inventory differences; ^{233}U fission events yield about twice as much ^{90}Sr as ^{239}Pu fission events. Table III gives the fractional contributions of several key elements to radioactive ingestion hazards after 100,000 years of cooling for the thorium and DU systems; the magnitude of radioactive ingestion hazard from thorium and DU are roughly equal at that point in time.

TABLE III. Thorium and DU waste radioactive ingestion hazard elemental contributions after 100,000 years of decay

Element	Fraction of Total Radioactive Ingestion Hazard	
	DU system	Thorium system
Pb	20.6%	16.8%
Po	2.9%	2.4%
Ra	69.6%	65.0%
Th	2.0%	11.8%
Other	4.8%	3.9%

Evaluation of a concept that cycles thorium fuel between a high flux fission power region and a low or zero flux "cooling" region that allows higher conversion rates of ^{233}Pa to ^{233}U could improve these waste disposal estimates since neutron capture in ^{233}Pa leads to ^{234}U and its decay chain, which includes the key nuclides ^{230}Th and ^{226}Ra. An analysis examining the expected radioactive dose to the public as a function of time, including release mechanisms and element-dependent solubility in groundwater, could provide more conclusive evidence of whether using thorium fuel reduces LIFE engine waste disposal risks.

No direct analysis of potential nonproliferation benefits of using a thorium fuel cycle instead of a DU fuel cycle in LIFE engines will be presented at this time. The thorium system produces significantly less ^{239}Pu but discharges higher inventories of ^{233}U and ^{235}U. Future studies will address these issues and others.

VII. CONCLUSIONS

Thorium fueling of a hybrid LIFE fission blanket has been demonstrated with performance comparable to that of a hybrid LIFE system fueled with DU under the constraints of a 40MT initial heavy metal loading, 30% TRISO packing fraction in the fuel pebbles, a total system power level of 2000 MW_{th} including 500 MW_{th} of fusion power, and the requirement of tritium self-sufficiency. Small but significant differences in decay heating, along with potentially large but much more complicated differences in radioactive ingestion hazards, have been demonstrated between fuel discharged from thorium and DU LIFE systems at the end of their plateau phase. Cycling the thorium fuel out of the high flux region intermittently to decrease parasitic neutron capture in ^{233}Pa, increasing ^{233}U production and decreasing ^{234}U production, could substantially reduce the radioactive ingestion hazard.

The thorium design described in this paper was guided and constrained by the desire to enable easy comparisons to an existing DU LIFE engine design; as such, multiple areas of improvement exist for a thorium fission blanket. Future work will include a parameter study to optimize the design, fuel performance analysis, and more explicit waste disposal and nonproliferation analyses. These calculations will inform design decisions on the optimal discharge burnup for thorium fuel and assess benefits offered by a thorium fuel cycle in these areas.

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